PROPERTIES OF THE SOLAR NEBULA AND THE ORIGIN OF THE MOON*

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Abstract. The basic geochemical model of the structure of the Moon proposed by Anderson, in which the Moon is formed by differentiation of the calcium, aluminium, titanium-rich inclusions in the Allende meteorite, is accepted, and the conditions for formation of this Moon within the solar nebula models of Cameron and Pine are discussed. The basic material condenses while iron remains in the gaseous phase, which places the formation of the Moon slightly inside the orbit of Mercury. Some condensed metallic iron is likely to enter the Moon in this position, and since the Moon is assembled at a very high temperature, it is likely to have been fully molten, so that the iron can remove the iridium from the silicate material and carry it down to form a small core. Interactions between the Moon and Mercury lead to the present rather eccentric Mercury orbit and to a much more eccentric orbit for the Moon, reaching past the orbit of the Earth, establishing conditions which are necessary for capture of the Moon by the Earth. In this orbit the Moon, no longer fully molten, will sweep up additional material containing iron oxide. This history accounts in principle for the two major ways in which the bulk composition of the Moon differs from that of the Allende inclusions.

1. Introduction

For many years H. C. Urey (see for example Urey, 1959) has sought to find in the properties of the primitive solar nebula conditions which could give rise to the peculiar composition of the Moon, prior to the assumed capture of the Moon by the Earth. The seemingly contradictory boundary conditions which must be satisfied are the extensive absence of the more volatile elements in the Moon and the lack of the usual content of iron, in view of the low bulk mean density of the Moon. Other authors (see, for example, Cameron, 1970; O'Keefe, 1970; Ringwood, 1970) have sought to satisfy these boundary conditions by postulating the formation of the Moon in some form in which chemical interaction of the Moon with the Earth is possible, resulting in the Earth obtaining most of the iron which would otherwise have gone into the interior of the Moon. None of these investigations has yet produced a consistent physical and geochemical picture of the origin of the Moon. Meanwhile, some progress has been made in capture theories, leading to the general conclusion that capture seems to be improbable but not impossible (Singer, 1970; Kaula, 1971).

Investigations of the properties of the returned lunar samples have been increasingly indicating that the outer layers of the Moon are composed of very refractory sub-

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stances, which will condense at the highest temperatures of any condensible materials in the solar nebula. This had led Gast (1972) to postulate that the outer layers of the Moon are primarily composed of these high temperature condensates. This picture has been extended by Anderson (1972, 1973) who has proposed that the entire Moon is composed of high temperature refractory materials, and in particular, the type of material which is present in the Allende carbonaceous chondrite as calcium, aluminum, and titanium-rich inclusions.

I consider these developments extremely promising, for they seem to indicate a location in the primitive solar nebula in which the composition of the Moon may find a natural explanation. This is a basic requirement for the validity of a lunar capture hypothesis.

Anderson assumed a number of conditions in the primitive solar nebula which are open to serious criticism, in his discussion of the manner in which the Moon might be formed out of high temperature condensates. In this paper I outline some of these criticisms, and then indicate how the Anderson hypothesis for the bulk composition of the Moon can be fitted into the models of the primitive solar nebula constructed by Cameron and Pine (1973).

2. The Anderson Model

Anderson has assumed that the Moon is formed at a distance of one astronomical unit from the Sun, but in an orbit of great inclination to the plane of the ecliptic, so that most of the obital trajectory would lie well away from the plane of the primitive solar nebula. He assumes that the black-body temperature at one astronomical unit from the Sun is maintained between 1300 and 1400 K, as a result of an assumed high-luminosity fully-convective Sun such as that postulated by Hayashi (Hayashi *et al.*, 1962), and calculated in some detail by Ezer and Cameron (1965). He assumes that the gas near the central plane of the solar nebula has a pressure between 10^{-1} and 10^{-2} atm, where the Earth is assumed to form, and he assumes that the Moon forms sufficiently high up above the central plane of the nebula that the average pressure in which the components condense is about 10^{-5} atm. A vertical column through the nebula is assumed to be isothermal. Under these conditions iron and magnesium silicates are condensed near the central plane of the nebula, but away from the central plane where the pressure is very low, the iron and magnesium silicates would not be condensed, but material characteristic of the calcium, aluminum, and titanium-rich inclusions in the Allende meteorite would be condensed. He assumes that the high temperature refractories can be assumed to form the Moon away from the central plane of the nebula, and that the Moon is subsequently captured by the Earth.

Let us first consider the postulated high luminosity stage of the Sun. This model of the Sun was first proposed by Hayashi, who pointed out that in a red giant star there is an upper limit to the effective radius of the envelope which is determined by surface opacities. Very low temperatures are not allowed, because the stellar opacity becomes too small, and self-consistent solutions for the envelope are not then possible. The only self-consistent solutions that arise in this situation are those of a fully or nearly fully convective interior, with the opacity of the radiative surface layers entirely governing the luminosity of the star. In studies of the pre-Main Sequence evolution of the Sun and stars of other masses, Ezer and Cameron have always included the high luminosity Hayashi portion of the track. The evolutionary time spent by a star in the high luminosity portion of the track is very small, and the interior adiabat which characterizes the structure of such a star is very high.

These evolutionary studies were not concerned with the manner in which a star would actually get onto the calculated evolutionary track. The first attempts in this direction consisted of the hydrodynamic studies of Hayashi (1966) and of Larson (1969), who computed the dynamical collapse history of stars of various masses within a collapsing interstellar gas cloud. Such stars were assumed to have no angular momentum. They found that a great deal of the released gravitational potential energy in the collapse was radiated away during the collapse phase, so that when a star was first formed, it was not formed in the high luminosity phase at all, but rather in the lower luminosity horizontal portion of the evolutionary track leading toward the main sequence. These studies have definitely ruled out the possibility of a high-luminosity phase of the Sun such as that required by Anderson in his model.

More recently, Perri and Cameron (1973) have shown that the adiabats assumed in the primitive solar models of Cameron and Pine (1973), as well as those that are consistent with meteoritic cosmothermometers and cosmobarometers, lead to the following conclusions. As the Sun is formed by dissipation in the solar nebula, with outward transport of angular momentum, and inward transport of mass, the adiabat, along which the compression of the mass at the center occurs, is considerably lower than the present adiabat at the center of the Sun. Hence the Sun derived in this fashion must reach the Main Sequence by a thermonuclear flash process initiating hydrogen burning. Such a flash process may cause a dynamical overshoot, bringing the Sun somewhat to the low temperature side of the Main Sequence, but its luminosity will be essentially that of the present Sun, except for the likelihood that the Sun at that time was more massive than the present one. A few tenths of a solar mass of material may be lost in the T Tauri phase of the Sun. Since the luminosity of a Main Sequence star near the mass of the Sun varies about as the fifth power of the mass, it is conceivable that the Sun actually had a luminosity two or three times as great as the present Sun when it commenced its T Tauri phase of mass loss. However, this represents the last stages of dissipation of the primitive solar nebula, and is certainly inconsistent with Anderson's picture in any case.

Next consider the possibility of accumulating a major body at a large height above the central plane of the solar nebula. It may be seen from the solar nebular models of Cameron and Pine that a pressure at midplane between 10^{-1} and 10^{-2} atm requires a surface density in the solar nebula of the order of 10^5 gm cm^{-2} column, or somewhat more. Any solid body in an orbit which takes it far above midplane of the nebula must pass through this plane twice per orbital period. It is evident that if the orbit is not to be drastically changed by gas drag, the projected mass per square centimeter column through the body must be 2 or more orders of magnitude greater than that in the primitive solar nebula. This implies a minimum projected mass of 10^7 gm cm^{-2} column, and a radius of at least 2×10^6 cm. Thus the minimum mass of such a body would be about 10^{20} g, which is about 10^{-6} of the Moon's mass and comparable to the mass of a major comet. Such a body would have to accumulate at a great height above midplane in the solar nebula in a time short compared to half of an orbital period. It must do this despite the fact that less than 10^{-3} of the total mass in a square centimeter column perpendicular to the plane of the nebula is available for formation of this primary condensate. Finally, many bodies of this type must gather together to form the Moon, without running into too many objects containing iron and magnesium silicates during the time that the bodies pass through midplane in the course of their orbits. I do not consider this to form an attractive hypothesis.

Finally, let us consider Anderson's hypothesis that the more refractory substances will be the only ones condensed at high altitude off the central plane of the nebula. This hypothesis depends heavily upon his assumption that the nebula is heated by a high luminosity Sun. In a solar nebula not so heated, the temperature gradient in the nebula is that which transports heat up to the nebular photosphere where it can be radiated into space. The temperature gradient may correspond to either convective transport of heat or radiative transfer, but in either case my own experience in constructing models of the solar nebula indicates that the less refractory substances become condensed nearer the nebular photosphere than near midplane. This is the opposite of Anderson's assumption. The reason is that relatively small differences in temperature can make a big difference as to the substances which are condensed, and to get a corresponding dependence upon pressure would require pressure differences of several orders of magnitude. Thus with a self-consistent structure of the solar nebula in which the temperature gradient transports heat to a nebular photosphere, the less refractory substances would be condensed at high altitude but not near midplane. In such a case, Anderson's hypothesis would have to take the form that the Moon was formed near midplane and the Earth was formed at a considerable distance above midplane.

However, although the solar nebula features associated with Anderson's model prove to be somewhat implausible, the basic geochemical analysis which he has carried out remains highly attractive, and it is therefore of some interest to see how this aspect of the hypothesis might fit into the solar nebular models constructed by Cameron and Pine.

3. The Cameron-Pine Models

In the Cameron-Pine models, the temperature in the primitive solar nebula arises from adiabatic compression of the gas which has collapsed from interstellar space to form the primitive solar nebula. The temperature and pressure fall off at midplane with increasing radial distance from the center of the nebula; the surface density of the nebula is maximum on the rotation axis, but there is no central star in hydrostatic equilibrium. At any point in the nebula, the initial temperature is the highest reached at any time in the thermal history of the nebula, neglecting circulation currents which modify this statement for particular elements of the gas. This means that the interstellar grains which are brought in with the gas to form the primitive solar nebula are not completely evaporated beyond some distance from the central spin axis in the nebula. The composition of the condensed material in the nebula follows, therefore, the usual sequence discussed for a cooling solar nebula, only the most refractory substances remaining in condensed form near the spin axis, and much more volatile elements remaining in condensed form at large distances from the spin axis. Cameron (1973) has discussed the problems of accumulation of planetary bodies within such a nebular model, and has concluded that it may be possible for planetary bodies to form in times of the order of a few thousand years.

According to an analysis by Lewis (1972), which is consistent with the primitive solar nebular models of Cameron and Pine, Mercury should form in a region where iron is condensed but not all of the magnesium silicates are condensed. Venus forms in a region where the magnesium silicates are condensed but the sulfur is still in gaseous form as H_2S. The Earth condenses in a region where the sulfur is added to the body in the form of metallic sulfides, thereby increasing the mean uncompressed density of the planet slightly, and Mars, having a considerably smaller uncompressed mean density, is also expected to have a considerable amount of water of crystallization.

The composition of the Moon, assumed to consist of the very high temperature refractory materials, is then consistent with formation as a separate body just inside the orbit of Mercury, where the metallic iron is no longer condensed. However, because the temperature difference between the complete evaporation of iron and the complete evaporation of the calcium, aluminum, and titantium oxides and silicates is only a few hundred degrees centigrade, the Moon cannot be formed very far inside the orbit of Mercury, or there would be no condensed substances present at all. Thus the relative spacing between the orbits of the Moon and Mercury would be significantly less than the relative spacing between the orbits of neighboring planets in the solar system today. This assures that there will be a prompt accumulation of gravitational perturbations between the two bodies in these orbits.

Anderson has discussed in considerable detail the way in which differentiation of the calcium, aluminum, and titanium-rich inclusions in the Allende meteorite can give the overall structure of the Moon. One anomaly in this analysis is the element iridium, which has a significant abundance in the Allende inclusions, but is highly depleted in the returned lunar samples.

It is unlikely that the Moon, when formed inside the orbit of Mercury, will not receive any content of metallic iron at all. Gravitational deflections of small bodies condensing near Mercury by Mercury should assure that some metallic iron will get into the Moon even if iron never condenses locally in the solar nebula before the nebula is removed at the place of formation of the Moon. Because the Moon must accumulate at an internal thermal temperature in excess of 1600 K, and because it probably accumulates fairly promptly, it is likely to have been a completely molten object at the time of its formation. The heat required to melt the Moon is easily obtained from the gravitational accretion process when the temperature of the accreting matter is already so high. The addition of metallic iron to this material will thus tend to scour out such siderophile elements as iridium from the rest of the material, allowing the metallic iron and nickel, with siderophile trace elements, to form a core at the center of the Moon. Such a core could have a radius of a few hundred kilometers without significantly affecting the measurements of the electrical conductivity in the lunar interior (C. P. Sonett, personal communication).

I have shown in another paper (Cameron, 1972) that if the orbit of Mercury is perturbed by the Moon so that it is transformed from a circular orbit at the present aphelion distance into the present orbit, enough energy is transferred to the perturbing body, having the mass of the Moon, to put it into an orbit which crosses that of the Earth. This is a primary prerequisite for any capture theory of the origin of the Moon, and it is difficult to think of any other way in which Mercury should have been able to obtain such a high fossil orbital eccentricity, equal to 0.206. There is no easy way to estimate when this orbital deflection might have taken place; it will have to be dated by specific evidence collected from the Moon itself.

Once the Moon is an orbit crossing that of the Earth, further perturbations of this orbit are likely to be caused principally by Venus and the Earth. To judge from calculations of meteoritic orbits, further major transformations in the lunar orbit can be expected on a time scale of the order of 10^8 yr. However, it is difficult for these perturbations to assist the capture process very much, since every time the Moon comes close to the Earth it will leave again, on an altered orbit, with essentially the same velocity of approach. Tidal retardation of the motion will ordinarily have little effect in any one close passage, and one cannot expect too many close hyperbolic passages without the Moon either colliding with the Earth or being deflected into an orbit which would cross that of Jupiter, after which Jupiter would control the motion of the Moon. However, if the Moon were to approach the Earth at a time of about 5×10^8 yr after the formation of the solar system, it is quite possible that the surface layers of the Earth may still be rather molten and viscous, so that the tidal phase lag may be increased over the present one and be much more effective in decelerating the relative motion of the Moon. These problems deserve close attention in further attempts to refine the lunar capture theory.

Another anomalous difference in the bulk composition of the Moon relative to the Allende inclusions is the presence of a considerable amount of iron oxide in the lunar samples. The iron which condenses at high temperature is the metal, and the oxide is not formed until the temperature in the solar nebula falls to about 500 K (Lewis, 1972). The Moon cannot have been expected to acquire the iron oxide at the place of its formation inside the orbit of Mercury. However, after being perturbed into an orbit which crosses that of the Earth, the Moon will capture a considerable amount of debris present in space before being captured by the Earth. By this time, perhaps of the order of 5×10^8 yr after formation, the central portion of the Moon may well have solidified, and only the upper layers may be near the melting point.

Thus the infall of additional material may result in the mixing of iron oxide only through the outermost layers of the Moon. Anderson has already shown that this sort of picture is consistent with the determination of electrical conductivity in the interior of the Moon.

4. Discussion

Anderson's hypothesis that the Moon is basically formed out of the type of material in Allende inclusions and has been completely differentiated throughout is very attractive to me. Although the astrophysical context in which Anderson formulated his theory seems rather improbable, the basic geochemical requirements of the theory seem to be quite consistent with the models of the primitive solar nebula constructed by Cameron and Pine.

I think that the problem faced by those trying to work out the dynamics of the capture of the Moon by the Earth is now better defined. It is clear that capture must start with the Moon approaching the Earth with a relative orbital velocity of several kilometers per second; this relative velocity must be reduced and ultimately eliminated by the dynamics of any capture process. It will be necessary to estimate tidal drag effects on hyperbolic passes of the Moon by the Earth, keeping in mind that the surface layers of the Earth may be far more plastic and viscous than they are at the present time, thereby increasing tidal phase lags and making tidal slowing processes more efficient.

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